Development and Application of Electroluminescence Imaging for CdS/CdTe Characterization

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ABSTRACT

A technique for spatially resolved electro-optical characterization of CdS/CdTe thin film solar cells has been developed using electroluminescence (EL). Light produced by radiative recombination of injected excess carriers is collected with a CCD camera. Because EL intensity depends upon radiative vs. non-radiative recombination lifetimes, it provides insight into material quality. Spatial resolution is a key benefit of EL imaging as it provides data on the in-plane non-uniformities in a cell. Data gathered from CdS/CdTe cells from various institutions deposited using different deposition methods and processing steps yielded differences in EL intensity and pattern. Furthermore, overall EL emission decreased noticeably with stress, with non-uniformity increasing in many cases. Changes in EL become apparent much earlier than changes in parameters acquired with standard current-voltage measurements, suggesting that this technique can be used as an early indicator for degrading cells.

1. Introduction

Advances in the performance and stability of thin film CdTe based solar cells have often relied heavily on the empirical approaches. To continue to make advances in the technology it is becoming more important to develop a better understanding of the fundamental processes and material properties behind cell performance and stability.

One inherent property in any device based on polycrystalline thin film is some degree of nonuniformity of the photo-electronic properties. This issue is considered important enough in the CdTe community that it is the focus of one of a handful of sub-groups formed from the CdTe national team. Standard photovoltaic characterization techniques such as current-voltage, capacitance-voltage, and quantum efficiency measurements average properties over the area of a solar cell. Contrasting with these methods is a new wave of spatially resolved characterization schemes such as cathodoluminescence [1,2], electron beam induced current [2,3], laser beam induced current [4], near-field scanning optical microscope photocurrent collection [5], photoluminescent mapping [6], and electroluminescence (EL), discussed here.

EL can be easily induced in CdS/CdTe devices by forward biasing a completed solar cell [7]. Though the excitation mechanism is different, EL is a similar technique to the more commonly employed photoluminescence (PL). Instead of optical excitation, excess electron-hole pairs are injected electrically. Their recombination produces luminescence. It is important to note that EL is not intended to replace PL but instead to complement it. The intensity of EL emission is roughly proportional to the product of the electron and hole concentrations. Because n-CdS is believed to be doped heavier than the p-CdTe absorber layer, the n×p product reaches a maximum in the CdTe near the junction. Thus, this location is where we believe EL originates. Our previous spectral studies of EL are consistent with this analysis [7]. Furthermore, EL spectra have been found to be similar to PL spectra in CdTe [7] as shown previously for many other materials such as SrS:Cu and SrS:Ag,Cu,Ga thin films [8], Si^+-implanted SiO_2 [9], CdS nanocrystals [10], and $Si_{1-x}Ge_x$ alloys [11]. This similarity lends further credence to the usefulness of EL and PL as complementary techniques and the ability to use information from one to explain effects in the other.

There are several advantages of EL making it attractive as a characterization technique. Though our EL technique (described below) does not have the highest spatial resolution among the techniques listed above, the range of resolved EL data may be the greatest, with a linear resolution of several microns to scans of over a centimeter. Also, unlike other methods that usually involve high injection rates, the degree of excitation required to induce measurable EL is only on the order of J_{sc}. In other words, the conditions that produce EL are comparable to the conditions of a device in normal operation. This moderate excitation level increases confidence in the idea that observations of EL patterns can be related to cell performance. EL gives insight into material quality because recombination centers degrade EL emission cell efficiency alike. Furthermore, low injection ensures that characterization will not degrade device performance (as verified by I-V data taken before and after EL imaging). As a final point, EL is technically simple to perform as it can be observed at room temperature and data acquisition is relatively quick. Because it is simple to implement, EL may find use as a standard production monitoring tool in an industrial application.

2. Experimental details

Biasing used to induce EL is provided by a Keithley 2120 3A SourceMeter®. This device also allows for I-V curves to be measured without moving the cell from the EL apparatus. EL Images are acquired with a Santa Barbara Instrument Group ST-5C cooled CCD camera that has a 320×240 array of 10×10 μm^2 square pixels. The cell is mounted on a micrometer-controlled stage and imaged through either a 1.3× or 10× microscope objective. The 10× objective allows for resolution on the order of the optical limit for the infra-red EL, namely several microns. The 1.3× lens images a 1.6×1.2 mm^2 rectangular area of a cell. Multiple images can then be stitched together graphically to form a composite of the entire cell. Cells to be compared are imaged at constant

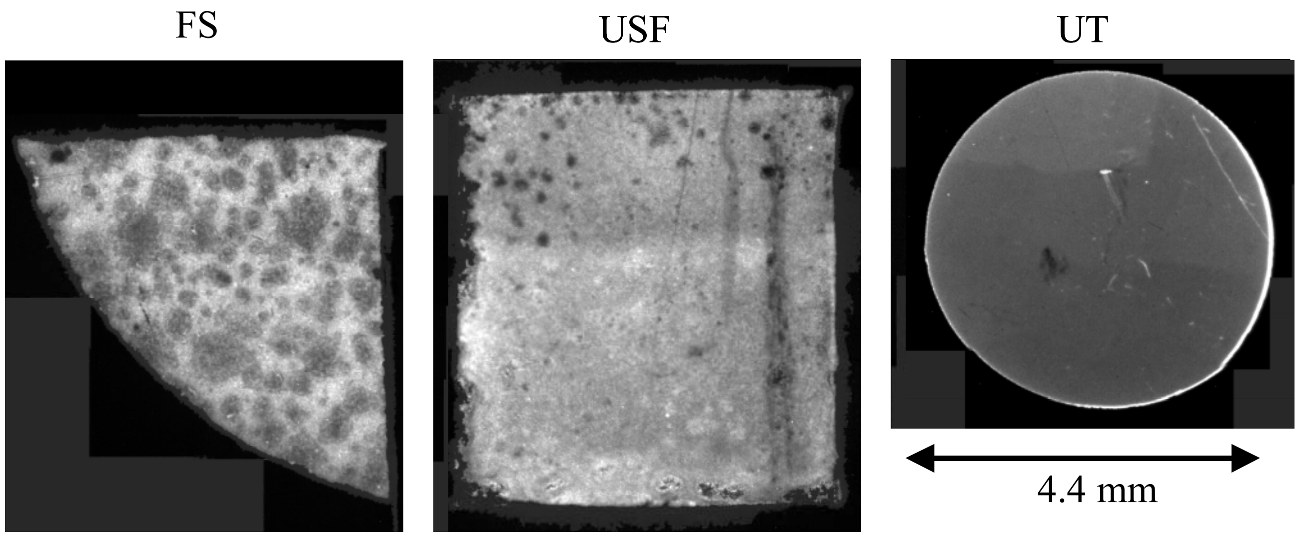

Figure 1. Composite, low magnification EL images. All have the same scale in dimensions but not brightness. Differences in total EL intensity did not exceed ~30 %. Note, the FS cell was scribed from a circle into a sector to approximate the area of the UT cell while still showing the edge of the original cell. Current density ≅ 33 mA/cm^2 for all images.

current density as noted below, and standard CCD acquisition time is 60 seconds for all data shown.

Image data is numerical, consisting of a 320×240 array of numbers with each number representing the photon count at each pixel. The simplest piece of information that can be drawn from this data is the mean EL intensity. Exploiting the spatially resolved nature of the measurement allows one to characterize the nonuniformity in the EL emission. A simple parameter called the "nonuniformity" is defined as the standard deviation of EL intensity normalized by the mean EL intensity. Generally, trends in this parameter mirrors qualitative observation made from the CCD images. In order to further characterize the nonuniformity (manifested by the distribution of brightness), a histogram of pixel intensity is employed. A normal histogram distribution looks gaussian. However, many images possess a non-gaussian distribution, e.g. multiple, overlapping populations or a long, lorentzian-like tail at higher brightnesses.

3. Results

Above, Fig.1 shows stitched EL images of cells from First Solar (FS), University of South Florida (USF), and University of Toledo (UT), manufactured with different deposition techniques (vapor transport, close-space sublimation, and sputtering, respectively) and back contacts (proprietary, Ag paste, and Au, respectively). Though mean emission intensity was comparable, pattern and degree of nonuniformity varied greatly from institution to institution. The uniformity parameters for the cells were FS: 0.22, USF: 0.15, and UT: 0.11.

Comparison of the low resolution image of the UT cell in Fig.1 to the highly magnified image of the same cell in Fig. 2 below, reveals the most striking example of nonuniformity on different scales. Differences in nonuniformity are quantitatively shown with histograms in Fig 3. Note how the low magnification UT image has the narrowest histogram (indicating that it is the most uniform), whereas the FS histogram is significantly wider. The difference in width and shape of the low and high magnification UT histograms is indicative of the small-scale nonuniformity. Also, the FS histogram has a peak with a shoulder, indicating two separate populations. This corresponds to the observed light and dark regions of the cell.

Other studies have focused on changes in EL emission due to specific processing changes. First, a study was conducted using cells with First Solar (FS) material whose back contacts (ZnTe:Cu/Au) were processed at CSM. EL from cells that underwent $CdCl_2$ treatment was compared to EL from nominally identical cells without $CdCl_2$ treatment. Both sets of cells showed isolated bright spots less than 20 microns in size whose background emission was indistinguishable with the dark counts (Fig. 4). The cells with Cl had more bright spots, and spot intensity was

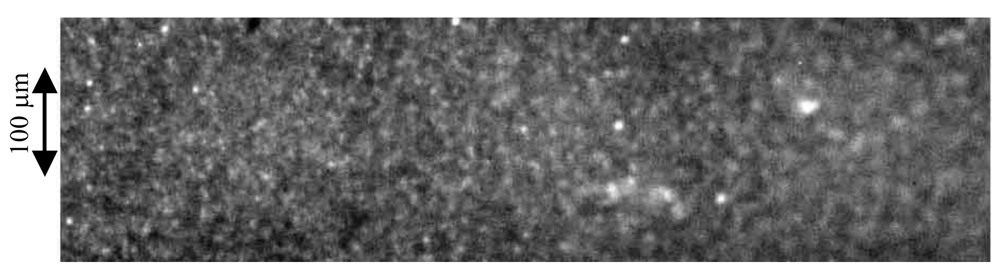

Figure 2. High magnification image of UT cell shown in Fig. 1, above. Resolution ~5 µm. Current density ≅ 33 mA/cm^2.

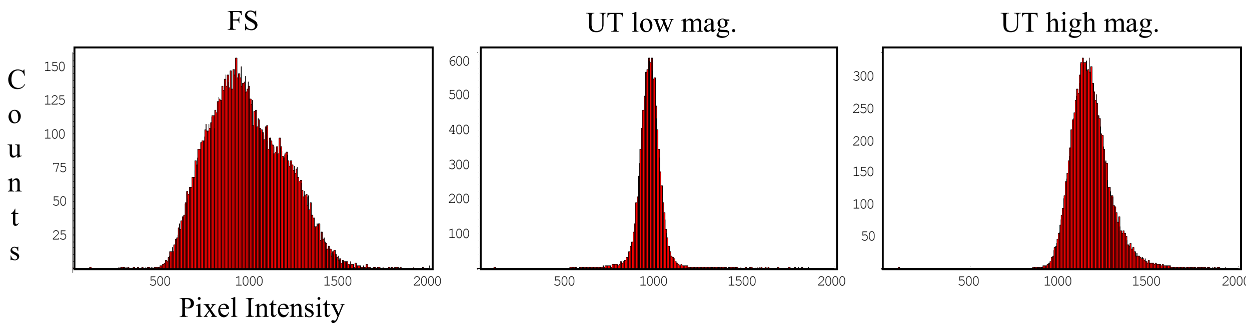

Figure 3. Selected Histograms

greater. Furthermore, the rate of increase of EL intensity with current was lower in the cells without Cl. Drive level capacitance profiling was also used to estimate the deep level density in these cells [12]. It was found that the cells subjected to the Cl treatment possessed more traps than the cells without $CdCl_2$ treatment. This result was unexpected, as a greater trap concentration would imply less luminescent recombination, but is important nonetheless because it proves that effects of Cl treatment (a crucial step for producing efficient CdTe devices) can be observed with EL.

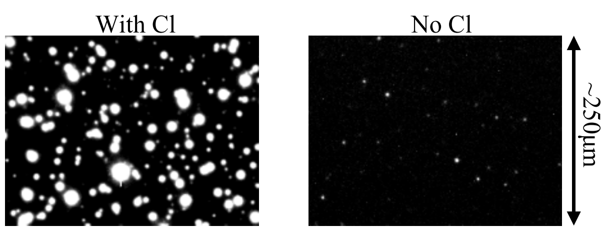

Figure 4: effects of $CdCl_2$ treatment on EL. Current density ≅ 50 mA/cm^2.

EL in cells from Colorado State University (CSU) was found to be profoundly influenced by the concentration of Cu in the cell. This experiment was conducted as part of a study with the CdTe national team involving a set of stressed and unstressed cells with varying amounts of Cu. The stressed cells were light soaked at 100^{o}C under open circuit condition for four weeks.

Despite noticeable degradation such as drops in FF, CSU cells showed little change in EL due to stress. However, this result is not too surprising in light of the fact that the CSU cells showed very dim emission initially. In contrast, there was a noticeable change in EL (both in intensity and pattern) due to the presence of Cu. The cells were processed with 0, 0.5, 1, and 4 minutes of Cu vapor deposition. The most brightly emitting cells were those with the 0.5 and 1 min of Cu. These cells also demonstrated the most non-uniform EL intensity. Compared to these two processing conditions, 4 min of Cu lead to a small decrease in emission intensity (less than a factor of 2) as well as an increase in uniformity. The cells with no Cu showed a ~4x decrease in emission intensity and also slightly increased uniformity compared to those cells with Cu.

Though spectrally resolved EL emission of these cells might yield information on the cause of the observed change in the intensity and non-uniformity with respect to Cu content, EL spectra could not be obtained due to low signal strength.

In general, the observed response of EL to stress has been a dramatic drop in EL intensity with amounts of stress that did not degrade efficiency much at all. Compaan *et al.* have also observed a similar effect [13]. This drop in emission intensity is usually accompanied by an increase in non-uniformity. These huge changes in the short term suggest that EL can perhaps be used as an early warning system for detecting cells that are likely to degrade quickly. One possible mechanism in which implementing this technique would be useful is explained here. Romero *et al.* showed that one distinguishing factor between "good" and "bad" material is faster Cu diffusion through grain boundaries in bad material [1]. Furthermore, Tang *et al.* demonstrated that diffusion of Cu away from the back of the cell raises the

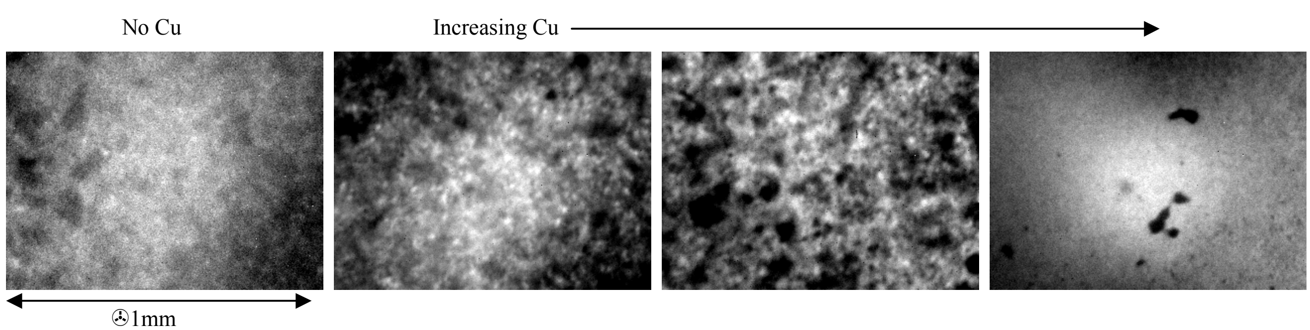

Figure 5. Unstressed CSU cells. The amount of Cu content in the cells imaged from left to right is 0, 0.5, 1,and 4 min, respectively. Note, despite appearances, the image of the cell with no Cu is actually ~5x less bright than those containing Cu. The contrast has been adjusted so that the image can be viewed easily. (An evenly adjusted image would just look black.) Current density ≅ 600 mA/cm^2.

back contact barrier [14]. EL studies on lightly stressed material could possibly reveal the difference between a good and bad batch of modules without having to wait months in the field.

As a final point, recent attempts to characterize the scale of non-uniformities have lead to the employment of variograms. The variogram is a geo-statistical technique used to quantify the spatial correlation of data [15]. The degree of this spatial correlation helps to quantify the scale and possible anisotropies in the non-uniformity structures underlying electroluminescence. For example, a feature size of ~10 μm was found in the UT cells discussed above.

4. Conclusions

EL images have been obtained of CdTe solar cells at high (several microns) spatial resolution with low current injection levels (on the order of J_{sc}). Non-uniform patterns have been shown to occur at different scales on differently grown cells, suggesting that perhaps different physical models should be used when interpreting the data for different materials. EL is also affected by changes in important processing steps, namely $CdCl_2$ treatment and Cu doping before or along with application of the back contact. Accordingly, EL may be able to help unravel the effects of Cl and may aid in finding how to stop Cu from leaving the back contact. Finally, even gently stressed cells have shown drastically affected EL intensity. EL may prove useful in an industrial setting because of its possible ability to predict long-term stability based upon short term stress data. This non-destructive testing technique has met some success with GaP LEDs [16].

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